High data-rate laser transmitters for free-space laser communications

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ABSTRACT

Master-oscillator power-amplifier (MOPA) laser systems, for future lasercom terminals to be flown in space are being developed and characterized. These lasers fall into groups for applications in deep space and near earth (including GEO) orbiting satellites. For deep space applications a diode pumped Q-switched Nd:YVO_4 oscillator and a multi-pass Nd:YAG amplifier laser with an average output power of 1.5 W and capable of supporting repetition rates of 100 KHz was studied. This laser emits at 1064 nm and was tested with pulse position modulation at data rates of 400 Kbps. The laser pulse width (~ 2 ns FWHM) and timing jitter (+/- 8 ns) are reported with relevant discussions pertaining to deep space performance. For near earth applications, a two stage diode pumped fiber amplifier system providing 1072 nm emission with 4 W of average power and capable of supporting data rates of 2.5 Gbps is briefly described. A second semiconductor flared amplifier system emitting at 980 nm has also been developed and is awaiting characterization.

1.0 INTRODUCTION

The NASA, Jet Propulsion Laboratory (JPL) is pursuing the development and characterization of high data rate lasers which meet the requirements for direct-detection free-space laser communications. For deep space communications, where maximum photon efficiency is desired, lasers and modulation schemes to minimize the average to peak power ratios are sought, while holding the average power constant. Solid state Q-switched lasers with high peak power and low duty cycle, are ideally suited for such applications. On the other hand, for low earth and geostationary orbits (LEO & GEO) optical links, maximum data rates are desired, channel capacity[1] can be achieved with relatively high average to peak power ratio. Semiconductor lasers which can support high bandwidth modulation are suitable for these requirements.

In this paper we report on pulse position modulation (PPM) testing of a master oscillator power amplifier (MOPA) solid state laser, delivered to JPL under a Phase II, Small Business Initiative Research (SBIR) contract, by Lightwave Electronics Corporation. This laser consists of a diode pumped low power Q-switched Nd:YVO_4 oscillator[2] feeding a multi-pass diode pumped Nd:YAG amplifier[3].

In 1998, Spectra Diode Laboratories (SDL), under SBIR, Phase II contract, has delivered: (i) a MOPA based on a Yb-doped 2-stage fiber amplified laser, emitting 4W at 1072 nm. with modulation rates of 2.5 Gbps and (ii) a semiconductor flared amplifier laser emitting 1W at 980 nm and capable of supporting 2.5 Gbps. We will provide a brief description of these systems.

In section 2 below we present some characterization studies performed with the solid state laser and PPM. In section 3 we present some discussions of semiconductor MOPA lasers for free-space laser communications.

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2.0 Nd:YVO4 LASER STUDIES

2.1 Experimental arrangement used for PPM testing

The solid state MOPA consists of a Nd:YVO4 oscillator which emits 1.5 μJ Q-switched pulses at a 50 KHz repetition rate. Even though the laser is capable of supporting 100 KHz repetition rates, the tests described in this report use 50 KHz since this repetition frequency was compatible with the PPM modulator used. The oscillator pulses are amplified by the multi-pass amplifier to yield an average output power of 1.5 W at 1064 nm. A JPL developed PPM modulator using a Xilinx XC26216-2 field programmable gated array (FPGA) was used for the tests to be described. Figure 1 shows the experimental setup while Figure 2 shows a schematic view of the 256-ary PPM scheme which uses slot widths of 20 ns. A small fraction of the 1064 nm light transmitted through a high reflectivity coated mirror (not shown) was subjected to attenuation with neutral density filters (ND 7.8 -9.3) before focusing the light on the detector. Several different types of detectors which are listed in Table 1 below, were used.

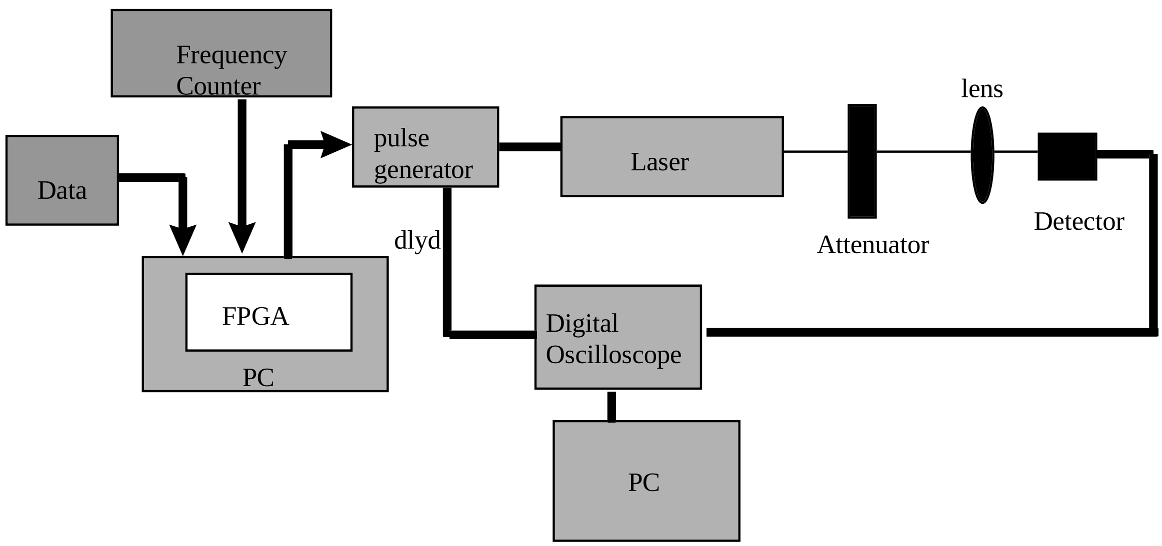


Figure 1 Showing a block diagram of the setup used for performing the PPM characterization

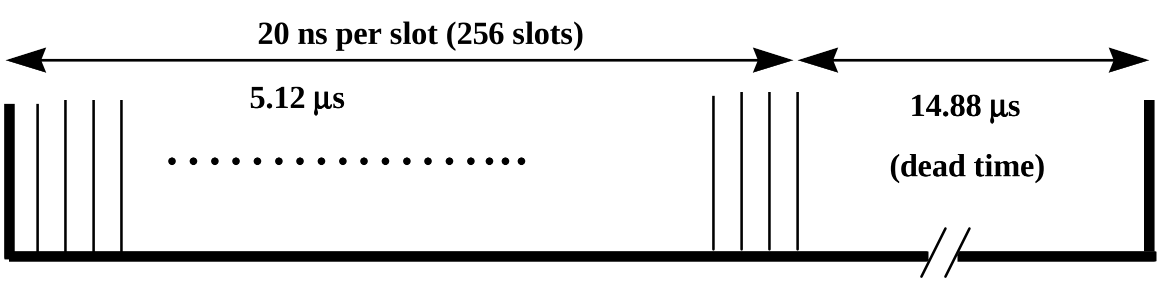


Figure 2 Showing the 256-ary PPM word length corresponding to a 50 KHz laser pulse repetition frequency

Table 1 listing the characteristics of some of the detectors used

Detector	Bandwidth	Area (μm)	Quantum Efficiency
InGaAs PIN	1.0 GHz	100	~78%
Si APD	500 MHz	500	4-5%
Si SPCM	-	120	2%

The focused spot size obtained with our setup was ~ 80 μm, measured using a CCD camera and frame grabber controlled with beam analysis software.

An 8-bit word, output from a data generator was fed to the FPGA and converted to a PPM pulse. This pulse triggered the pulse generator. The pulse generator triggered by the PPM pulse, was programmed to output two pulses, one of these pulses triggered the laser oscillator, and the second pulse is delayed. The delayed pulse and the laser pulse output from the detector were each recorded on two different channels of the digital oscilloscope. The delay on the PPM pulse recorded by the oscilloscope was adjusted so that it was displayed more or less synchronously with the laser pulse. The digital oscilloscope we used has a buffer of 8 million points. Thus, using a 500 MHz sampling rate on the oscilloscope we were able to store two channels of 8 ms duration each, or a single channel with a sequence lasting 16 ms.

2.2 Results

The statistical behavior of the laser pulse width and jitter behavior was studied by looking at many single pulses. Figure 3 shows a histogram of the pulse width and the pulse jitter. The pulse jitter distribution is shown as the pulse peak position with respect to the mean position.

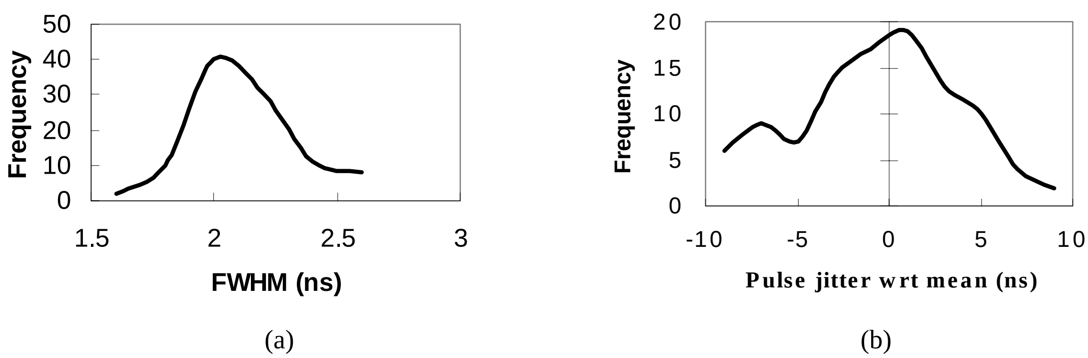


Figure 3 Showing the distribution of (a) the full-width half maximum (FWHM) laser pulse and (b) the pulse jitter shown as the position of the pulse peak with respect to the mean position.

Assuming a Gaussian fit to the distributions shown in Figure 3, >99% of the time the laser pulse will fall within the 20 ns slot width. The pulse jitter we believe, is electronic in nature and can possibly be lowered by synchronizing the laser trigger pulse with the RF driver in the laser oscillator. We have not explored this option yet. Given the laser pulse jitter measured it is apparent that the minimum slot width required is 20 ns.

Figure 4 shows a 50 μs duration sequence of PPM generated laser pulses, along with the delayed PPM pulse for reference. Figure 5 shows how the measured laser pulse peaks compared with the predicted positions based on the output of the data generator. Thus, if the laser output pulses followed the predicted data input exactly then all the data points would be at zero. The observed deviation ranges from -2 to 8 ns. Given the pulse FWHM of ~ 2ns all these pulses fall well within the slot width as expected.

We attenuated the laser pulse in order to obtain an estimate of the sensitivity of the detectors shown in Table 1. We found that the Si APD was sensitive to the level of 200-300 photons per pulse while still being able to provide PPM signal above the background and detector noise levels. The InGaAs PIN detector sensitivity was on the order of 11000 photons per pulse and was limited by the noise and lack of gain. The SPCM APD according to our measurements was sensitive to ~600 photons per pulse. Random occurrences of dark pulses from the SPCM output which we measured at an average of 80-100 counts per second (cps), can confuse the PPM scheme since these dark pulses are identical in appearance to the signal pulses and can occur, in principle, at any time including the dead time. By cooling to -30°C the dark counts can be reduced to 8 cps[5].

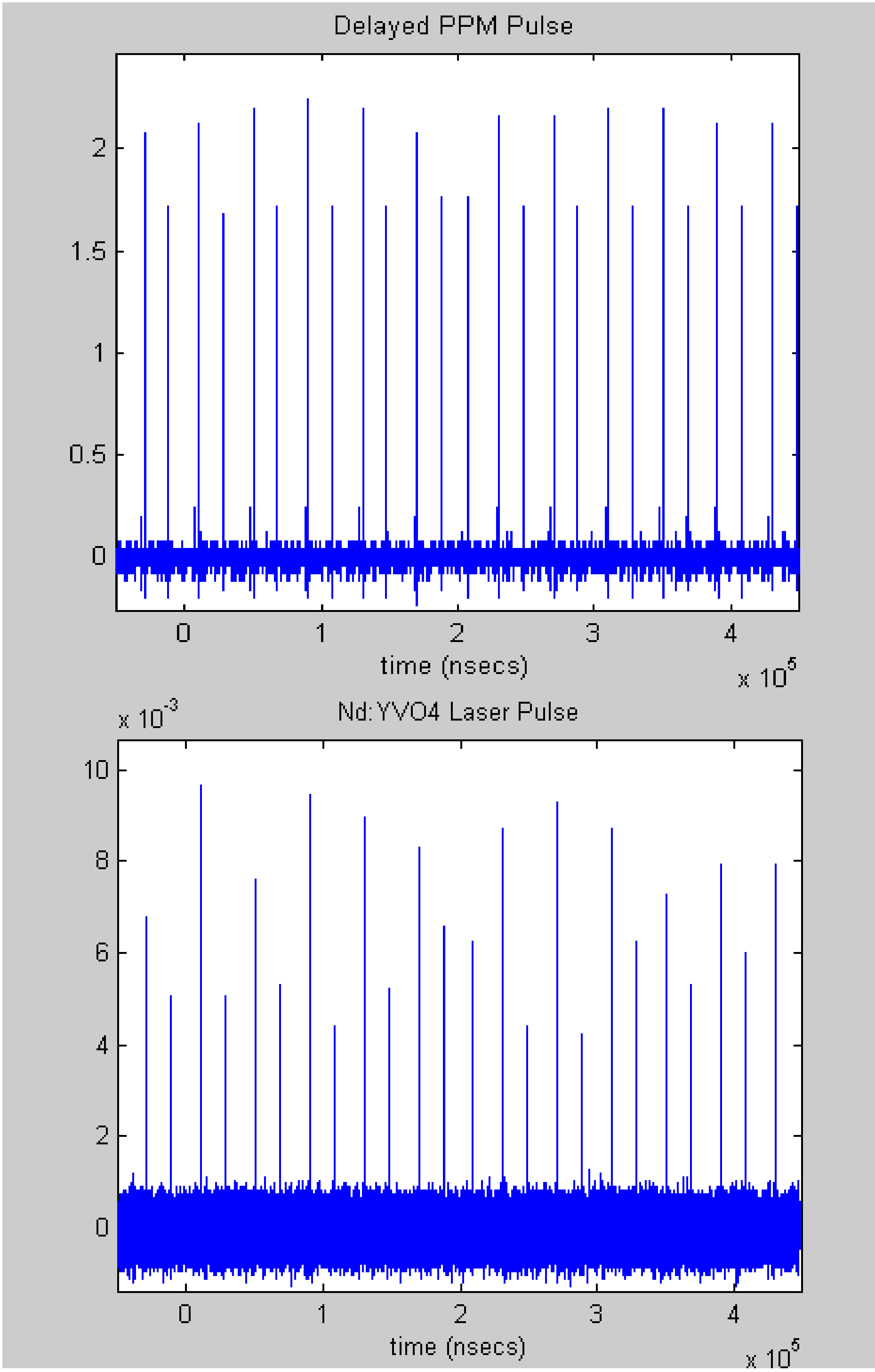


Figure 4 Showing a 50 μs duration sequence of the PPM generated laser pulses along with the delayed PPM pulses for reference

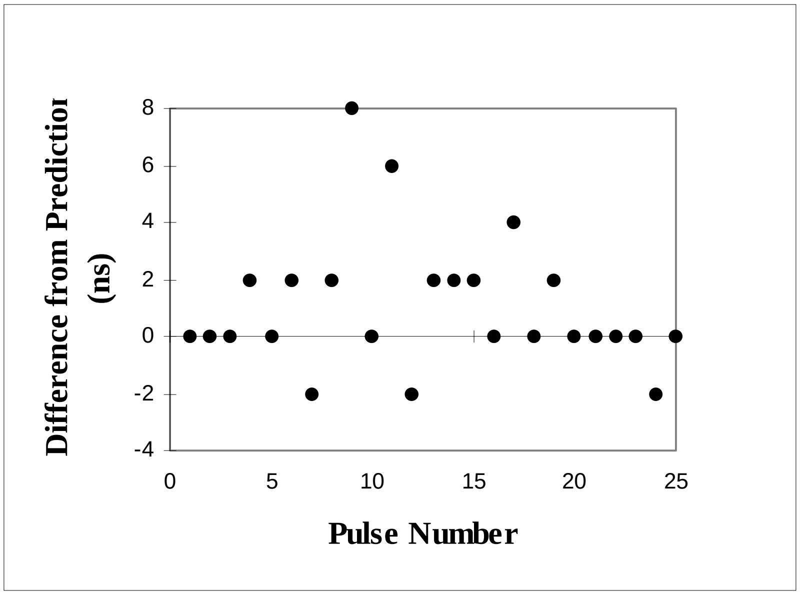


Figure 5 Showing the deviation in pulse peak positions of the PPM modulated laser tested. The predicted pulse peak positions for a perfect modulation scheme would lie on the horizontal line marked zero on the ordinate.

2.3 Discussions

The laser characteristics discussed above show the pulse jitter behavior of a candidate prototype solid state candidate laser for deep space communciations applications. Assuming that the pulse jitter could be improved in order to allow the use of a 10 ns slot width instead of 20 ns, the background photons/slot could be reduced by half. As an example, we can consider a day time Mars link analysis performed using FOCAS[4]. Using a 5 W laser transmitted through a 30 cm aperture telescope from a 2.51 AU distance under day time conditions and collecting the signal on the ground with a 10 m telescope would allow >1 dB extra link margin by lowering the slot width from 20 to 10 ns, all other conditions remaining the same. This example was based on a 50 KHz repetition rate laser with a 256-ary PPM and a data rate of 400 Kbps. This additional dB of margin could, for example, be used to increase the data rate to 500 Kbps with 62.5 KHz laser repetition rate assuming that the pulse jitter and width do not change.

Based on FOCAS link analysis we know that the signal return from Mars at 2.51 AU using a 1.5 W laser transmitting through a 30 cm aperture telescope and received using a 10 m telescope on the ground under typical clear atmospheric conditions, results in a signal of ~350 photons per pulse. The 1064 nm wavelength though suitable from considerations based on high peak power to average power ratios, affords poor sensitivity for Si detectors. It is not clear whether higher quantum efficiency InGaAs detectors can provide the gain and low noise characteristics desired for deep space applications. Therefore, suitable detectors at 1064 nm satisfying the bandwidth and sensitivity requirements deserves urgent attention. Alternate wavelength lasers which do not compromise any of the 1064 nm solid state laser characteristics but afford higher sensitivity to Si detectors, also deserve careful thought.

On the issue of data rates, we desire both lower (1-5 KHz) and higher pulse repetition rates but do not want the average-to-peak power ratios to increase. Thus, with higher repetition rate the pulse width would have to be narrower and all the other performance characteristics such as pulse width and jitter would have to remain the same or improve.

Finally power conversion efficiency is crucial for the successful use of deep space laser communications. The solid state laser described in this report could under the best of circumstances approach a 10% electrical to optical conversion efficiency. Future technology developments must try to identify methods of improving upon this in order to make optical communications competitive with other approaches for deep space communications.

3.0 SEMICONDUCTOR MOPA LASERS

As pointed out earlier these are usually the high average power/peak power ratio lasers which can be modulated at extremely high data rates.

3.1 Yb-doped fiber amplified MOPA
Figure 6 shows the photograph of a Yb-doped fiber amplifier transmitter assembly along with a Nd:doped receiver assembly. This was developed by SDL Inc.

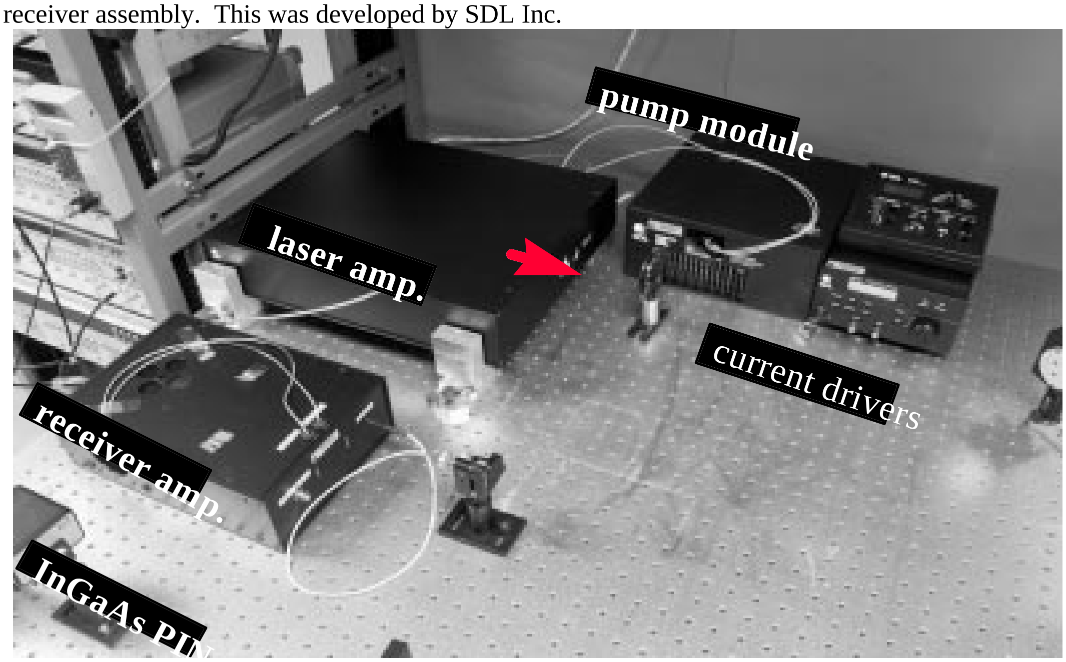


Figure 6 Showing the fiber amplified MOPA assembly delivered to JPL under Phase II SBIR contract by SDL Inc.

Figure 7 shows a schematic block diagram of this assembly. The transmitter consists of a low current/power Fabry-Perot laser diode oscillator, with a matching 50 ohm resistor in series and capable of supporting 2.5 Gbps modulation rates. This diode emits at 1072 nm. Fiber coupled light from this oscillator after isolation (not shown) is fed to the first stage pre-amplifier consisting of 12 m length Yb-doped double clad fiber which is pumped at 920 nm. The second stage power amplifier utilizes a 15 m lenght Yb-doped double clad fiber. Also shown in Figure 7 is the Nd-doped fiber amplifier receiver assembly.

We measured the power output of this laser while using 2.1 A of current for the pre-amplifier pump lasers and 25 A for the power amplifier pumps. The diode laser oscillator was biased with 27 mA and modulated by a pseudo-random bit sequence at 1-3 Gbps. The output power was 4 W. However we did observe as much as a 25% fluctuation in output power levels and this is still under investigation.

Figure 8 shows the beam profile measured at the free-space coupled output end of the fiber amplifier. Figure 9 shows typical eye-patterns observed, before and after performing clock and data recovery, as displayed by a oscilloscope.

3.2 Semiconductor flared amplifier
A 1W 2.5 Gbps diffraction limited flared amplifier source emitting at 980 nm was recently delivered by SDL Inc. to JPL. Figure 10 shows a photograph of this laser. The master oscillator used for this laser is a fiber coupled diode laser capable of emitting 20 mW of optical power. This master oscillator is capable of supporting 10 Gbps of modulation. The flared amplifier boosted the power to 1 W while supporting 2.5 Gbps

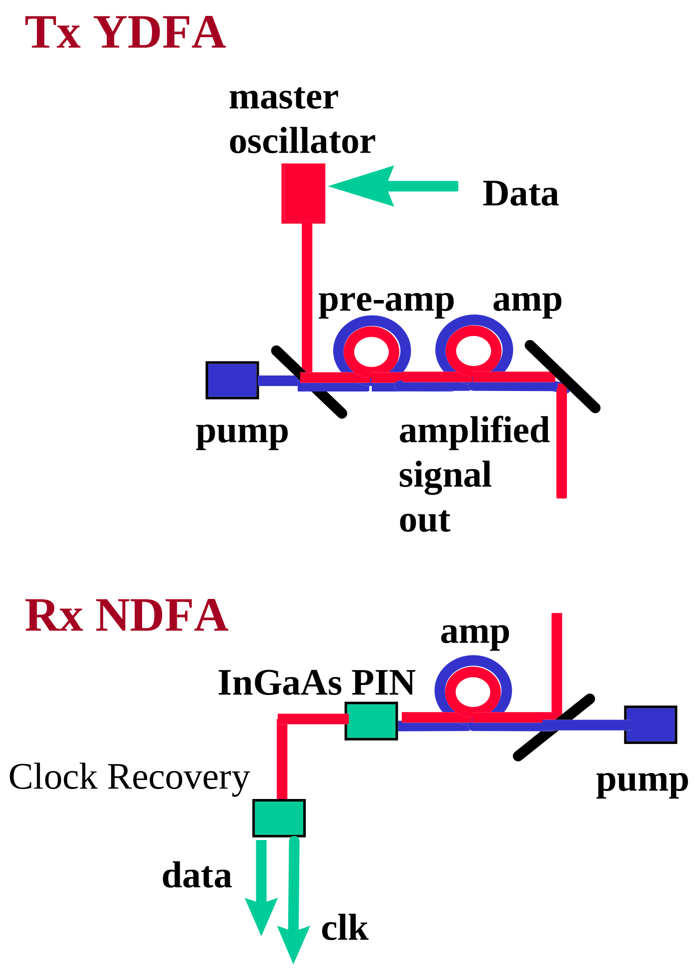


Figure 7 Showing a schematic block diagram of the transmit receive fiber amplifier MOPA assembly. 920 nm light is used to pump the first and second stage Yb-doped fiber amplifier. The receiver pump uses 808 nm light into a Nd-doped fiber amplifier.

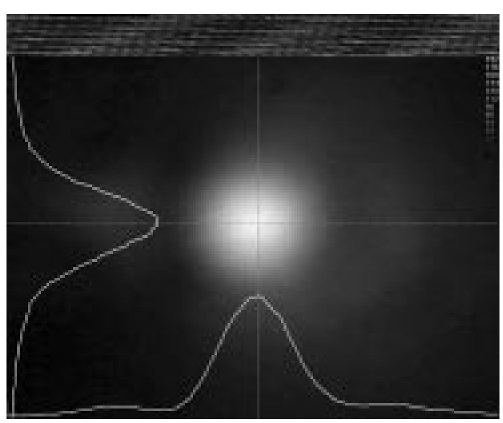
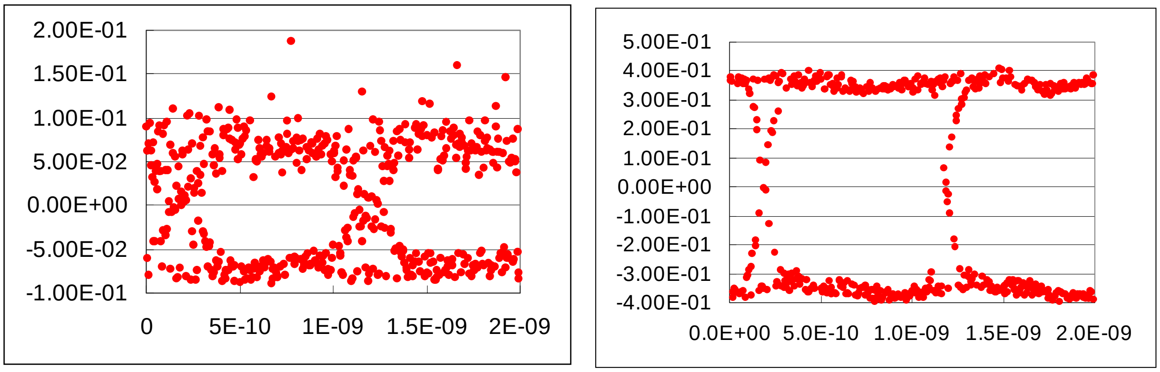


Figure 8 Showing the beam profile at the free-space coupled output end of the laser amplifier.



(a) ***(b)***

Figure 9 Showing the measured eye-patterns using an InGaAs PIN detector with the laser being modulated at 1 Gbps (a) the output from the PIN directly viewed on the oscilloscope and (b) eye-pattern viewed after performing clock and data recovery with a Broad Band Communication Products (BCP) Model 500 A Clock and data recovery unit.

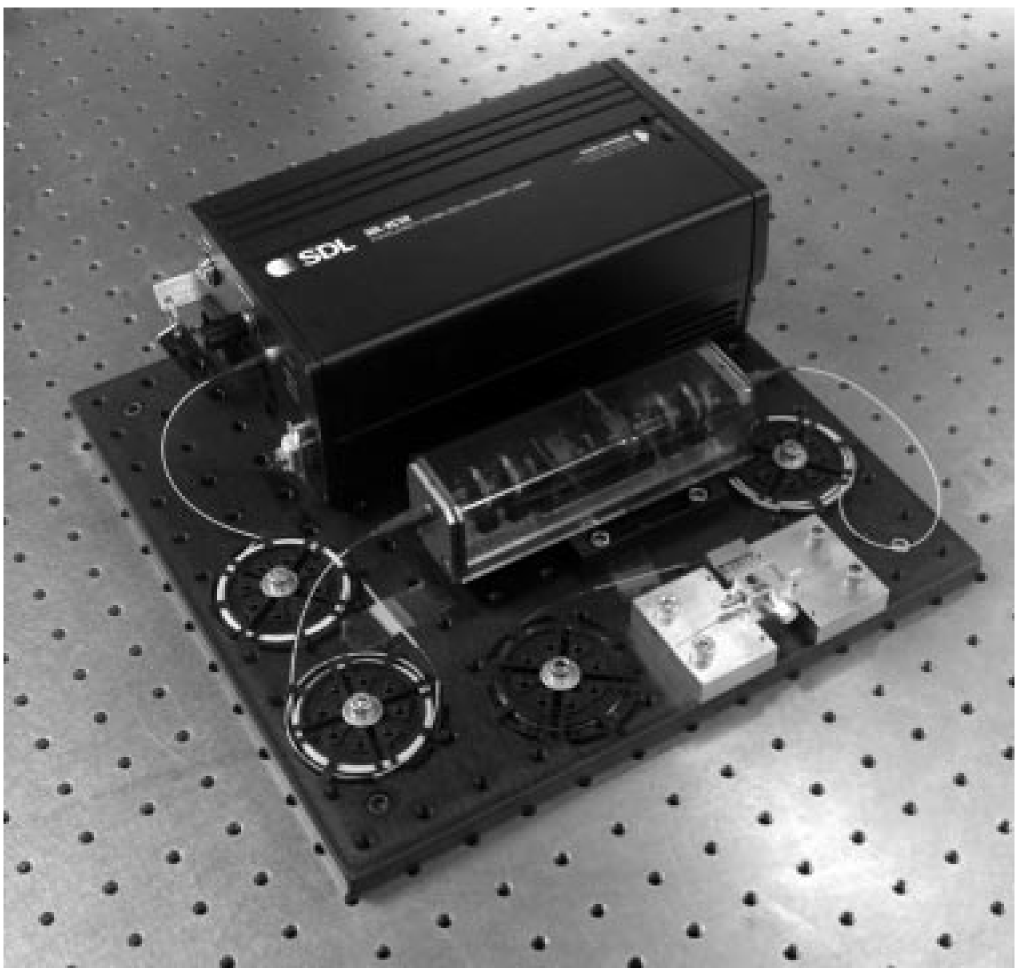


Figure 10 Shows the semiconductor flared amplifier laser delivered to JPL by SDL Inc.

4.0 CONCLUSION

In conclusion we have presented some data on PPM characterization of a prototype laboratory version of a solid state MOPA laser. The laser pulse width and jitter were measured and shown to require a 20 ns slot for a 256-ary PPM modulation scheme. By improving the pulse jitter the slot width could potentially be reduced to 10 ns providing additional link margin or allowing the possibility of higher data rates for the same margin. Data to show the performance of the laser under 256-ary PPM was presented along with some measured estimates of the sensitivity with which the pulses could be detected using a few different types of detectors. We plan in the future to include an InGaAs APD and photomultiplier tube (PMT) in our characterization studies. Some of the issues relevant to deep space communication lasers such as the pulse repetition rates, operating wavelengths and electrical-optical conversion efficiencies were discussed.

Some recent developments in the area of semiconductor MOPA's were described with very preliminary measurements. We expect to provide a full characterization report of these lasers in the future.

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